Steam generation by sunlight traps

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Abstract
A preliminary study of a boiler generating superheated steam by means of solar power is presented. Steam generation in this system does not need convection fluids, which in general are utilized in traditional solar thermal systems. The apparatus is conceived by considering the idea of sunlight trap, consisting of a sunlight collector and a black body.

Keywords: Solar energy, Thermodynamics.

Resumen
Se presenta un estudio preliminar de una caldera de vapor sobrecalentado a través de la energía solar. generación de vapor en este sistema no necesita fluidos por convección, que en general se utilizan en los sistemas tradicionales de energía solar térmica. El aparato está concebido considerando la idea de atrapar la luz solar, que consiste en un colector solar y un cuerpo negro.

Palabras clave: Energía solar, Termodinámica.

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I. INTRODUCTION

In the perspective of sustainable development of countries not yet at a fully industrialized stage and in the effort of converting the productive processes to methods based on renewable energies in the industrialized world, solar energy plays an important role. Among all types of alternative energies, solar energy is the one with the highest level of availability on Earth. It can be esteemed that it could be technically possible, in the future, to utilize a radiating power of about 60 TW from the Sun [1]. The power generated at the present is about 0.008 TW, which is only a small fraction of the actual world power demand of about 12.5 TW [2]. Since this figure will tend to increase in the future (it is thought that the world power demand will be of 16.9 TW in 2030), nowadays various types of innovative solar power plants have been proposed.

Among the most commonly known types of solar power plants, we may recall the ones utilizing highly reflecting parabolic troughs to collect solar radiation on a pipe running along the linear focus of these special mirrors [3]. In the Archimedes project [4], in particular, the temperature of the superconducting steam generated is about 550°C. In this case, however, a convective fluid with a high temperature of fusion is utilized, while in other systems [5] steam is directly generated inside the pipe running along the linear focus of the parabolic collectors. In the latter case, however, lower temperatures of the superheated steam are achieved.

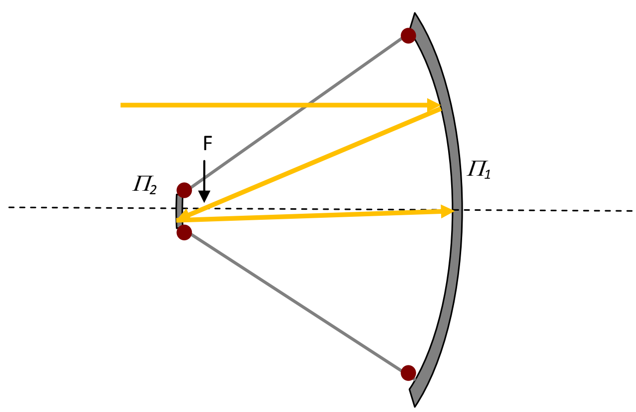

FIGURE 1. Light rays coming from infinity are collected by the primary parabolic mirror Π_1 and sent to the secondary mirror Π_2 (hyperbolic or ellipsoidal in shape) passing through the common focus *F*. After reflection on Π_2 , light rays are concentrated close to the vertex of the primary mirror, where a heavy duty light guide is placed.

Concentrating solar radiation in a small region of space presents further advantages. As shown by De Luca *et al*. [6, 7], sunlight can be trapped by means of a two-mirror system coupled to a black body. In the composite optical system, the first mirror is a parabolic collector (primary mirror), the second, facing the primary mirror and having a focus in common with it, is rather small in size and of hyperbolic or ellipsoidal shape. In this way, light rays collected by the primary mirror are first sent to the secondary mirror, which, in its turn, reflects them back to the vertex of the primary, as schematically shown in Figure 1. Close to the vertex of the primary mirror a heavy duty light guide is placed, in order to convey the collected solar radiation into a black body.

In the present work, the concept of sunlight trap is extended to steam generators which could work with solar energy. The system is designed in such a way that steam at a fixed temperature and pressure is produced, even in the presence of time-dependent radiating power coming from the optical system. One of the characteristic features of this device, indeed, consists in the fact that the source of heat is time dependent. In this way, it can be shown that the quantity of vapor that can be generated in a given interval of time at a given pressure and temperature is itself a time-dependent quantity which is proportional to the power delivered to the system by solar irradiation. The rather random variation in time of the energy source over intervals of the order of some minutes, or at most of few hours, constitute a limitation on industrial applications of this device. However, the sunlight trap concept can constitute a good starting point for future research on environmental safe applications of solar thermal systems.

II. THE SOLAR STEAM GENERATOR

In this section the way in which steam is generated in a boiler, utilizing solar radiation as the heat source, is described. The solar steam generator can be conceived as a series of two-mirror optical systems, all connected to a hollow cylindrical column as in Figure 2.

The cylinder sustaining the parabolic collectors has highly reflecting inner walls, in such a way that it may be considered to be a black body. Inside this cavity a black metallic coaxial hollow cylinder is placed (see Figure 3). In this inner metallic cylinder, having external walls with high transmission coefficient for incident light rays, water is pumped in from the bottom, in such a way that the radiation power absorbed by the cylinder itself is transferred, by conduction, to water. It is then clear that, in this way, solar energy can be transferred to water without the aid of a convection fluid. By letting the temperature rise in the cylinder, as we shall see in details in what follows, superheated steam may be generated.

The parabolic mirrors, placed on the oblique cylindrical column as shown in Figure 2, are always oriented toward the sun by means of a high precision sun tracking system. As described in the Introduction, therefore, solar radiation is first trapped and then utilized to generate superheated steam inside the inner metallic cylinder, as pictorially shown in Figure 3.

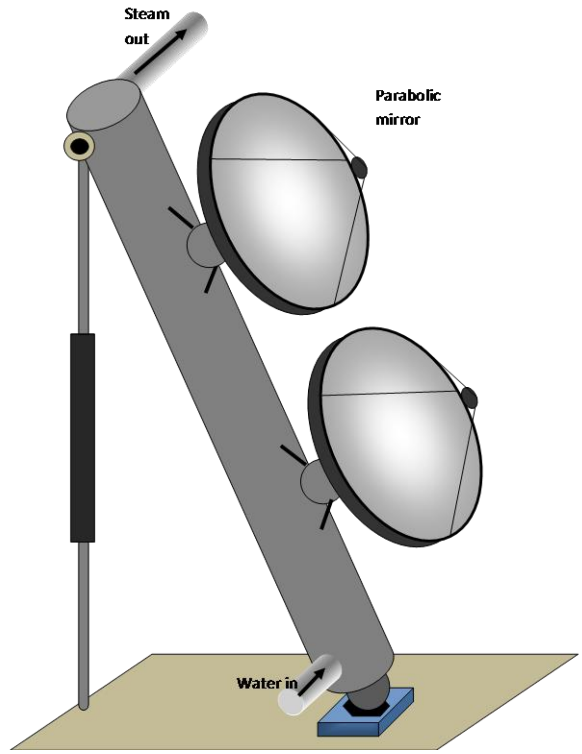

FIGURE 2. Schematic representation of the device. The parabolic mirrors are placed on the sides of a hollow cylinder with highly reflecting inner walls (black body). Water goes into the inner cylinder through the pipe shown in the bottom. Vapor comes out from the pipe on the top. The parabolic primary mirrors are oriented by a sun-tracking system, in such a way that optimal exposition to direct sunlight is always achieved. If a single-axis tracking system is used, the inclination of the cylindrical column should be controlled in time.

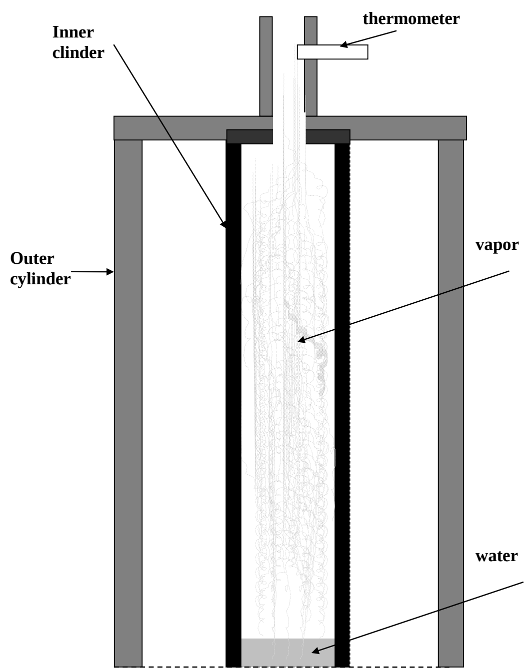

FIGURE 3. A section of the inner and outer cylinders in the solar steam generator.

In the region close to the vertex of the primary mirror a light guide may be inserted, in order to couple the optical system with the inner portion of the black body. This is a rather critical portion of the system, since it might easily reach very high temperatures.

The radiant energy trapped in the black body is thus utilized to first heat water to its boiling temperature T_b at pressure p_C in the boiler, then to generate steam at T_b and, finally, to heat steam from T_b to the final temperature T_f. In practice, we imagine that air is present between the outer cylinder and the coaxial metal cylinder placed inside. Solar radiation is thus effectively trapped in the hollow space between the two coaxial cylinders and it transfers heat predominantly to the inner cylinder. Water inside the inner cylinder is heated by conduction. It is therefore important to have highly absorbing outer surfaces for the inner cylinder.

Assume now that a mass Δm of water flows inside the boiler in the time interval Δt, in such a way that the quality of the superheated steam is left unaltered. We shall see that, in general, the pressure p_C and the temperature T_f. can be kept constant in the boiler only if we renounce to the condition of constant output flow of vapor from the boiler. This is a consequence of the fact that the power input, coming from sunlight, is not necessarily constant over the operation period of the boiler.

III. THERMODYNAMICS OF THE SOLAR BOILER

A solar boiler works in much the same way as an ordinary boiler does. Nevertheless, sunlight is available only during daytime and solar radiation reaches the Earth surface with more or less intensity, depending on the hour of the day, on the period of the year and of the local meteorological conditions. This time-dependent character of the source of heat leads to a flux of superheated steam of a given quality, as we shall see, not constant in time.

Let us consider an isobaric transformation, occurring at pressure p_C, by which the mass of water m entering the boiler at temperature T_0 is brought to the boiling temperature T_b. The quantity of heat Q_1 necessary to raise the temperature of water from T_0 to T_b is thus

$$Q_1 = mC_1(T_b - T_0), \tag{1}$$

where C_1 is the heat capacity of liquid water. In order to get vapor at T_b, we need to spend an additional quantity of heat λ for each unit of mass of water (latent heat of vaporization), so that

$$Q_2 = m\lambda \ , \tag{2}$$

is the heat necessary to transform the mass m of water at T_b into vapor. Finally, in order to get vapor at temperature T_f, an additional quantity of heat Q_3 is necessary, so that

$$Q_3 = m\int_{T_b}^{T_f} C_p(T)\mathrm{d}T = m\overline{C}_p(T_f - T_b), \tag{3}$$

where $C_p(T)$ is the temperature-dependent specific heat at constant pressure of vapor and $\overline{C}_p$ is its average value over the temperature interval (T_b, T_f). The total heat Q_T required to accomplish the overall transformation is thus

$$Q_T = Q_1 + Q_2 + Q_3 = m\left[C_1(T_b - T_0) + \lambda + \overline{C}_p(T_f - T_b)\right]. \tag{4}$$

The above quantity of heat is provided by sunlight radiation, so that, by denoting with P the effective power transferred to the boiler, we have

$$P = \dot{Q}_T = \dot{m}\left[C_1(T_b - T_0) + \lambda + \overline{C}_p(T_f - T_b)\right], \tag{5}$$

where the dot stands for "derivative with respect to time" and where the quantity

$$\alpha_T = C_1(T_b - T_0) + \lambda + \overline{C}_p(T_f - T_b) \tag{6}$$

is assumed to be constant. In this way, after a first transient, we may envision the following working conditions of the device. In fact, if an instantaneous power $P(t)$ comes from solar radiation, the mass rate which can flow at time t in the boiler, without changing the vapor quality, is given by

$$\dot{m}(t) = \frac{P(t)}{\alpha_T}. \tag{7}$$

As previously stated, the mass rate is directly proportional to the instantaneous power input, which, on its turn, is not necessarily constant in time. Nevertheless, in regions where solar radiation power density is constant over a rather prolonged portion of the day, it is possible to envision a steady-state regime for the steam generator, characterized by the condition

$$\dot{m}(t) = \text{constant}. \tag{8}$$

In order to fix our ideas, let us assume that in a partly cloudy day a power density of 500 W/m^2 can be intercepted by the device. This figure is about one half of the peak value attainable in a sunny day. For a single parabola, with effective surface S = 10 m^2, the power we can transfer to the boiler is equal to 5 kW. If a total of five parabolas were mounted on the cylindrical pole, a thermal power of 25 kW would be available. Therefore, a solar power plant consisting of 100 poles, each containing five parabolas, would give a total thermal power of 2.5 MW, with peak production of 5.0 MW. In order to utilize this thermal power for electrical purposes, one would need to multiply this quantity by the efficiency of the turbine system converting the thermal power available from the solar plant into electric power.

Notice that the above analysis is valid only if we consider the temperatures T_f and T_0 and the pressure p_C and, as a consequence, the temperature T_b, as constants. In this case, in fact, Eq. (7) holds and a direct proportionality between the vapor output rate from the device and the input power is realized. In the case the system is in its initial state, its evolution to the working stage needs to be calculated by considering the types of materials chosen for the various parts, the particular form of the function *P(t)*, and the geometrical characteristics of the device. All these aspects are common to solar collectors, which are nowadays object of intense research, as it happens, for example, at Plataforma Solar de Almeria, in Spain [5].

According to the author, the conceptual advantages given by sunlight trapping systems are not negligible. First of all, the temperature T_f can be chosen to be greater than the working temperature of traditional systems, in which the heat exchange from the pipes (containing water or the convection fluid) to the environment is a rather stringent limiting factor. In the case of sunlight traps, on the other hand, the cylindrical hollow column can be considered, in principle, to be a black body. In this way, all radiant power intercepted by the collector can be utilized to produce steam. Furthermore, being energy an extensive physical quantity and being the system able, at least on a conceptual ground, to collect radiant energy continuously in a given interval of time Δt, the final temperature would depend on the amount of energy ΔE, given by

$$\Delta E = \int_0^{\Delta t} P(t)\mathrm{d}t. \tag{9}$$

After a sufficiently long transient interval of time Δt has elapsed, so that the desired final temperature T_f is reached inside the boiler, the working condition (7) can be attained. Notice also that, according to (6) and (7), the vapor flow rate depends inversely on the temperature T_f.

A second non-negligible advantage is the possibility to have a lower impact on ground occupation by these types of devices, when compared to traditional thermal solar systems, by the simple fact that an effective three-dimensional arrangement of these columns can be envisioned, as shown in Figure 2. Of course, one could study a useful way of integrating hypothetical future power plants, based on sunlight trapping systems, with agricultural use of the surrounding ground.

IV. CONCLUSIONS

The concept of sunlight trap [6], consisting of a two-mirror solar collector and a black body, has been adopted to conceptually develop a solar steam generator. In this solar boiler, after a transient interval of time, necessary to reach the working conditions of the device, the quantity of overheated vapor generated in the unit time is proportional to the solar radiant power *P* the optical system is able to transfer to the boiler at time *t*. This aspect could limit the fields of application of the device conceived in the present work, especially when one consider the traditional industrial use of electrical or thermal power. In order to overcome this problem, it could be possible to first store the energy produced, preferably with environmental safe methods, and then to utilize it in more controlled ways.

The device proposed in the present work provides some conceptual advantages with respect to traditional thermal solar systems. First of all, one notices that in traditional sunlight troughs the pipe running along the linear focus, containing water (for direct steam generation) or a convection fluid, is exposed to air. In sunlight traps, on the other hand, water is contained in a metallic cylindrical nucleus inside the cylindrical black body. In this way, the working temperatures T_f of the latter systems can be chosen to be higher than those in traditional systems. As an additional advantage, one can mention a more rational use of ground space of these devices and the possibility of integrating thermal power generation with agricultural usage of the surrounding area in hypothetical future electrical power plants based on sunlight trapping devices.

Other applications of the sunlight trapping concept are conceivable. For example, desalination of seawater can be obtained by spray-drying this liquid on sunlight-heated absorbing metal blocks placed inside a black body similar to the one depicted in Figure 2. In this case, however, the metal block would separate the front air chamber, in which light is trapped, and the back chamber, in which salt water is sprayed on the other side of the block. In this way, vapor is formed and collected as in Figure 2 and salt falls because of gravity at the bottom of the back chamber.

As a final remark, one can hypothesize that technical problems may arise in the realization of a prototype of the solar boiler described in the present work, mainly because we have adopted rather idealized schemes. In this respect, the most delicate point is represented by the optical coupling of the black body and the two-mirror system. However, by following principles and ideas set forth in the present analysis, one could be confident that fabrication problems may be solved and sunlight trapping could be realized for an extensive and more rational use of solar energy on Earth.

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